Acceleration Sensors of Smartphones

Possibilities and Examples of Experiments for Application in Physics Lessons

Patrik Vogt[1], Jochen Kuhn[2]

[1]Dept. of Physics, University of Education Freiburg
[2]Dept. of Physics/Physics Education Group, University of Kaiserslautern
[1]Kunzenweg 21, 79117 Freiburg, Germany; [2]Erwin-Schrödinger-Str. 46, 67663 Kaiserslautern, Germany
[1]patrik.vogt@ph-freiburg.de; [2]kuhn@physik.uni-kl.de

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Abstract

Alongside well-known negative effects on everyday school life, cell phones can be used to enhance physics instruction in many ways: for example, to document and analyze experiments using the camera, to exchange data using various interfaces, to carry out Internet research or to use the cell phone as a measurement and experiment tool. This article focuses on the latter property and makes suggestions as to how the acceleration sensors integrated in smartphones can be used to conduct quantitative experiments in the field of dynamics, including, amongst others, descriptions of experiments investigating an inclined plane, free-fall, simple and coupled pendulums as well as radial acceleration.

Keywords

Smartphone Physics; Experimental Tools; Acceleration Sensor

Introduction

Smartphones–modern cell phones with enhanced computer functionality–are usually equipped with a microphone as well as a number of other sensors: acceleration and field strength sensors, a density of light sensor and a GPS receiver. As all the sensors can be read by appropriate software (apps), a large number of quantitative school experiments can be conducted with smartphones. This article focuses on this subject, providing suggestions as to how a smartphone can be used to improve mechanics lessons, in particular when used as an accelerometer [1]. An essential advantage of cable-free acceleration sensors is evident, as previously described from Scheler and Wilhelm (2009) with regard to radio sensors manufactured by Phywe and Pasco: As neither a cable connecting the sensor and the computer nor a connection to a motion transformer is necessary, the accelerations can be measured without any disturbance. Another advantage of the smartphone as an experiment tool is that it is simple to use. Pupils are familiar with the device and the apps that can be operated intuitively. Experts predict that conventional cell phones will have disappeared completely from the market in a few years. By then at the latest, the pupils will all possess an own "measurement data acquisition system", available for lessons at school or at home and, from our point of view, a valuable resource, for which useful applications should be developed and explored as soon as possible. The following article provides details on why acceleration sensors are integrated into smartphones and how they function. Understanding how acceleration sensors function is a necessary prerequisite in order to correctly interpret the measurements after having completed the experiments. These experiments are an integral part of the research program "Material-aided situated learning in physics instruction" conducted by the physics education department at Kaiserslautern (Kuhn et al., 2011). The project involves developing experiments with new everyday materials as well as performing the subsequent empirical study to explore the resulting learning and motivation outcomes in the context of a quasi-experimental test/control group study in physics lessons.

Acceleration Sensors in Smartphones

Controls via Tilting

A large number of smartphone applications are controlled by tilting the device. Examples of this are the "Real Racing" game (figure 1), in which the racing car can be sensitively steered by tilting the smartphone

[1] Alongside smartphones (such as the iPhone or Samsung Galaxy I5700, for example), an iPod touch can also be used for the experiments described in this article; it looks similar to the iPhone and offers similar functions, except for the telephone function.

(iHandy, 2012), "spirit levels", which specify the tilt angle to the horizontal exactly (iHandy, 2012), or the automatic adaptation of the program interface when the device is rotated by 90°. Applications of this kind raise the question as to how the tilt of a smartphone can be measured.

The tilt is measured by three sensors which determine the occurring accelerations with a measuring frequency of 100 Hz (in fact they are force sensors, i.e., the accelerations are measured indirectly; cf. next subsection). If the smartphone is motionless in the position shown in figure 2 (left), the device is affected by gravity only, i.e., the sensors in the direction of the *x* and *z* axes do not measure any acceleration, whereas the sensor in the direction of the *y* axis measures negative gravitational acceleration -*g*. If the device is rotated by the angle *α* within the x_y level, the situation changes fundamentally (figure 2, right). As the sensors and, as a result, the system of coordinates turn, the sensors in the direction of the *x* and *y* axes no longer measure zero, but the projection of gravity in the direction of the axes. Consequently, the following applies:

$$a_x = \sin(\alpha)\cdot g,\ a_y = -\cos(\alpha)\cdot g,\ a_z = 0\ \mathrm{ms}^{-2} \qquad (1)$$

(a_x, a_y, a_z acceleration in the direction of the *x*, *y*, and *z* axes). The apps described in the introduction read the data from the acceleration sensors, calculate the tilt of the device on the basis of the data and adapt the graphics of the display.

FIG. 1 SCREENSHOT OF THE GAME "REAL RACING", IN WHICH THE VEHICLE CAN BE CONTROLLED BY TILTING THE IPHONE OR IPOD

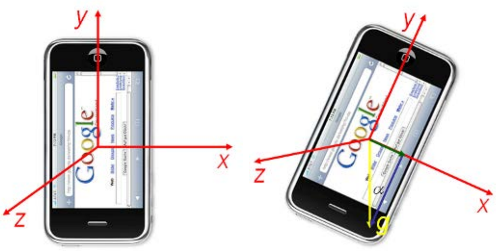

FIG. 2 THE DETERMINATION OF THE POSITION OF A SMARTPHONE FROM THE MEASURED ACCELERATION DATA; THE SENSORS MEASURE THE ACCELERATIONS IN THE DIRECTION OF THE MARKED AXES. (VOGT & KUHN, 2012a)

Mode of Operation of the Sensors

The way acceleration sensors function still has to be explained: they are micro-systems that process mechanical and electrical information, so-called micro-electro-mechanical-systems (MEMS). In the simplest case, an acceleration sensor consists of a seismic mass that is mounted on spiral springs and can therefore move freely in one direction. If an acceleration *a* takes effect in this direction, it causes the mass *m* to move by the distance *x*. This change in position can be measured with piezoresistive, piezoelectric or capacitive methods and is a measurement of the current acceleration (Glück, 2005). In most cases, however, the measurement is performed capacitively. Figure 3 shows a simplified design of a sensor of this kind: three silicon sheets which are disposed in parallel and connected to each other with spiral springs, make up a series connection of two capacitors. The two outer sheets are fixed; while the middle sheet which forms the seismic mass, is mobile. Acceleration causes the distance between the sheets to shift, leading to changes in capacity. These are measured and converted into an acceleration value. Strictly speaking, they are therefore not acceleration sensors, but force sensors.

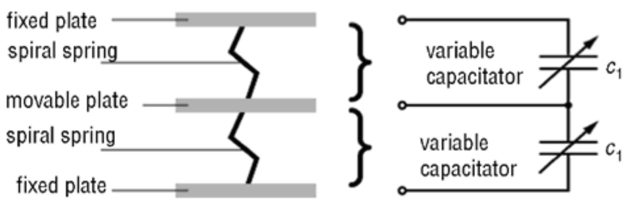

FIG. 3 SET-UP AND MODE OF OPERATION OF ACCELERATION SENSORS (SCHNABEL, 2012)

A Classical Dynamics Experiment with a New Experiment Tool

The Inclined Plane

The real-life experiment described in the following section demonstrates that the tilt of the smartphone can be very accurately determined on the basis of measured acceleration data. A smartphone is attached to an inclined plane with double-sided adhesive tape and the acceleration component *a* in the direction of the plane is measured using a suitable app[2]. This corresponds to the sine of the angle of inclination *α* multiplied by gravity *g*:

[2] In the experiments described in this article, SPARKvue software (Vogt et al., 2011) was used with an iPhone or an iPod touch; alternatively, the Accelogger app was used with an Android device.

$$a = \sin(\alpha)\cdot g \qquad (2)$$

Thus the following applies to the angle α

$$\alpha = \arcsin\left(\frac{a}{g}\right) \qquad (3)$$

The acceleration sensor has to be read in the direction of the y axis when performing the analysis of the experiment for the positions of the iPod shown in figure 4 and figure 5. The acceleration for the position shown in figure 4 is 2.51 ms^{-2}, which corresponds to a 14.8° angle according to equation 3. The acceleration for the tilt shown in figure 5 is 5.53 ms^{-2}, i.e., a 34.3° angle. Comparative measurements made with a set square supply 15° and 35° angles, thus matching well with the results of the experiment.

FIG. 4 ACCELERATION ON AN INCLINED PLANE WITH A SMALL ANGLE OF INCLINATION (α = 15°, MEASURED WITH A SET SQUARE)

FIG. 5 ACCELERATION ON AN INCLINED PLANE WITH A LARGE ANGLE OF INCLINATION (α = 35°)

TABLE 1 ACCELERATION IN THE DIRECTION OF THE PLANE DEPENDING ON THE ANGLE OF INCLINATION

α in degrees, measured with a set square	$\sin(\alpha)$	a in ms^{-2}, measured with an iPod
21.0	0.36	3.5
14.0	0.24	2.4
8.0	0.14	1.4
25.0	0.42	4.1
44.0	0.69	6.9
30.0	0.50	5.0
55.0	0.82	8.0
81.0	0.99	9.6

The results of a series of measurements can be seen in table 1. The removal of a against $\sin(\alpha)$ according to equation 2 results in a straight line, whose gradient corresponds to gravitational acceleration g (figure 6). The implementation of a linear regression confirms the assumed linear relationship with an adjusted coefficient of determination of 0.86 and delivers a gradient of 9.80 ms^{-2} for an insignificant y axis intercept, i.e., a figure that matches well with the acceleration of gravity.

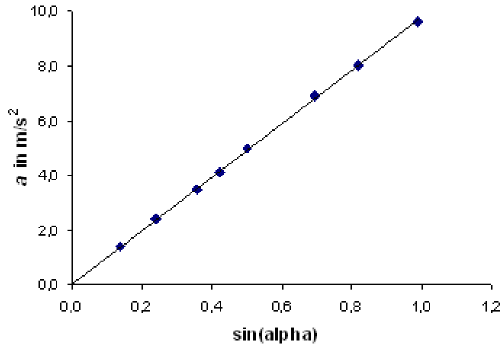

FIG. 6 REMOVAL OF THE ACCELERATION MEASURED BY THE IPOD AGAINST THE SINE OF THE MEASURED ANGLE RESULTS IN A HALF-LINE, WHOSE GRADIENT CORRESPONDS TO GRAVITATIONAL ACCELERATION

Free Fall

1) *In the Physics Laboratory or at Home*

A suitable way to examine free fall is to suspend a smartphone from a piece of string, which is burnt through to start the fall (Vogt & Kuhn, 2012a). In order to avoid damaging the device, a soft object is placed under the cell phone (e.g., a cushion) for it to land on. After having started the measurement of acceleration with a measurement frequency[3] of 100 Hz, the string is burnt through and the free fall commences. The acceleration value measured can be seen in figure 7.

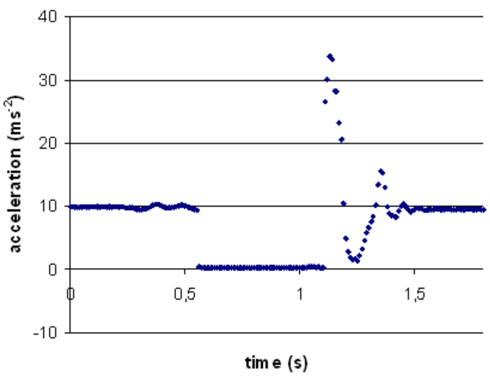

FIG. 7 ACCELERATION PROCESS OF A FREE FALL (VOGT & KUHN, 2012a)

[3] The measurement frequency is also 100 Hz for the pendulum experiments described and for the experiment for centripetal acceleration.

At first, the smartphone is suspended from the string and the acceleration of gravity of 9.81 ms^{-2} takes effect (left part of the diagram). After approx. 0.6 s, the free fall begins and the sensors cannot register any acceleration, because they are accelerated with 1 g themselves[4]. This state is maintained until the cell phone's fall is stopped by landing on the soft object. As it can be seen in figure 7 that the sensor continues to move slightly and returns to complete immobility after a period of 1.5 s. It is obvious that the smartphone has a dual function in this experiment as it serves both as falling body and as electronic gauge, making it possible to determine the free-fall time with a reasonable degree of accuracy. For the measurement example described, the falling time was calculated to be Δt = 0.56 s for a falling distance of s = 1.575 m. If these values are applied to the distance-time equation for uniform acceleration (without initial distance and initial speed and with the influence of the gravitational field for acceleration):

$$s = \frac{1}{2} g t^2 \tag{4}$$

The acceleration of gravity g is calculated with the formula

$$g = \frac{2s}{t^2} = (10,0 \pm 0,2)\frac{\mathrm{m}}{\mathrm{s}^2}, \tag{5}$$

delivering a sufficient degree of accuracy for school instruction.

2) *In a Recreation Park*

It is particularly interesting to investigate the free fall of a free-fall tower, which can sometimes be found in recreation parks. Figure 8 shows the free-fall tower at Holiday Park (Hassloch/Germany), which lifts three four-seat gondolas to a height of 62 m. After a short break, the free fall commences and brakes after a fall of 36.3 m (information provided by the operator). The acceleration process measured by the smartphone is illustrated in figure 9. Similar to the experiment of free fall over a short distance, the sensors first measure the acceleration of gravity, then during the fall record considerably lower values and, finally, record a high level of acceleration for the braking procedure. The fact that the accelerations during the fall are different to zero shows that the value of the acceleration of the fall is lower than gravitational acceleration and thus the fall is not completely free. Nevertheless, the "free-fall time" can be extracted from the data set (it is approx. 2.6 s in the measurement example). After applying equation (4), the free-fall distance is estimated to be 33 m. This result differs from the operator's information by 3.6 m, i.e., an approx. 10% deviation, and is considered acceptable for a school experiment.

FIG. 8 FREE-FALL TOWER IN HOLIDAY PARK (HASSLOCH)

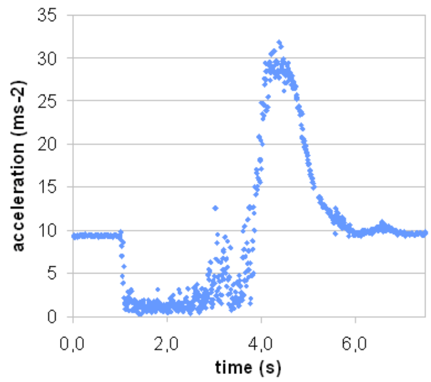

FIG. 9 ACCELERATION PROCESS OF A FREE-FALL TOWER

Alongside the free-fall tower, other rides in recreation parks can be analyzed in experiments with the help of acceleration sensors and provide learning opportunities for mechanics instruction (Schüttler & Wilhelm, 2011).

Pendulum Movements

In the following section, various pendulum experiments

[4] This is difficult to understand for pupils, because they perceive the exact opposite: At first, the device is suspended motionless from a string and then falls, accelerating to the floor. This is why they can only understand the measured acceleration process if they have previously been instructed on the way acceleration sensors function. In addition, the learners' previous experience of being pressed to the floor in a lift accelerating downwards, and the resulting conclusion that one is weightless in a free-falling lift, can also help them understand the process.

will be performed, in which a smartphone is used as a pendulum body. However, the following aspect should be emphasized before starting: if the lesson objective is to determine the period of an oscillation in an experiment, it is advisable to use a conventional stop watch rather than a smartphone. The use of a cell phone as pendulum body, however, generates a much greater quantity of information and more learning opportunities than the duration of a period alone and can greatly enhance instruction.

1) *The Mathematical Pendulum*

In order to perform an experiment that examines the laws governing a string pendulum, a smartphone can be suspended from two strings–this prevents rotation around the longitudinal axis (figure 10). Figure 11 shows a measurement example for a pendulum length l of 1.15 m (perpendicular distance between the center of mass of the iPod and the pivot point); and acceleration taking effect in the direction of the string is represented. The values measured constitute a basis for discussion of the following:

a) The accelerations measured in the direction of the string (figure 11); and why do the acceleration values vary around the acceleration of gravity and at what amplitudes are minimum and maximum displacement reached?

b) Determination of the period of a complete oscillation and comparison to the value theoretically expected.

c) Conversion of the tangential accelerations measured into pendulum amplitudes α or x with the help of a spreadsheet, in order to create a α-t or x-t diagram, which is easier for pupils to interpret.

d) Discussion of damping and calculation of the logarithmic decrement.

FIG. 10 IPOD SUSPENDED FROM TWO STRINGS (VOGT & KUHN, 2012b)

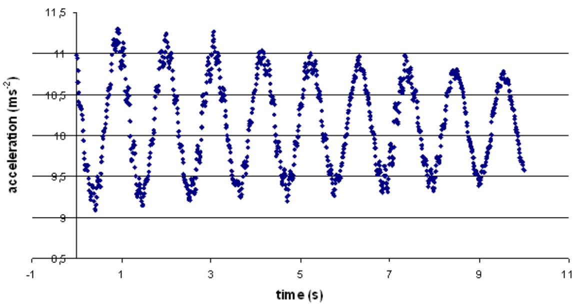

FIG. 11 ACCELERATION PROCESS FOR A MATHEMATICAL PENDULUM (L = 1.15 m) (VOGT & KUHN, 2012b)

At this point, the items a) and b) will be examined in more detail:

As regards a), the acceleration in the direction of the string is given by the sum of the centrifugal force apparently taking effect and the pendulum's mass in the direction of the string. As velocity is briefly zero at the turning point, the pendulum's mass only takes effect in the direction of the string at this point, so the acceleration of small g is measured. The minima of the acceleration curve (figure 11) are thus located at the turning points. When passing through the rest point, the pendulum is moving at its highest velocity and, as a result, at maximum centrifugal acceleration. In addition, the acceleration of gravity has to be completely added to it, i.e., the accelerations at the zero crossing point are higher than g and correspond to the maxima in figure 11. This observation makes it clear that the time lag between two peaks corresponds to half a period.

As regards b), the time lag between the first and ninth maximum (figure 11) is 8.61 s and corresponds to the time required for four complete swings. The period of the string pendulum's swing determined in the experiment is therefore 2.153 s with a measurement error of ±0.002 s. The duration of a complete swing T theoretically expected for a pendulum with a length l = 1.15 m is calculated with the formula

$$T = 2\pi\sqrt{\frac{l}{g}} \tag{6}$$

to be 2.15 s and therefore matching well with the result of the experiment.

Similar to the free-fall tower, it is interesting to explore the string pendulum and its oscillation process using a child-related everyday object, e.g., a children's swing. The particular appeal of this experiment is that the pupils can start by experiencing the acceleration with their own bodies.

On the basis of this experience, they can be asked to perform an assessment of the acceleration process, which subsequently can be quantitatively tested in an experiment. In order to carry out the experiment, the smartphone is fixed to the swing with adhesive tape with one axis pointing in the direction of tangential acceleration and the other axis in the direction of radial acceleration (figure 12).

FIG. 12 EXPLORATION OF THE MATHEMATICAL PENDULUM USING A CHILDREN'S SWING; THE IPOD IS FIXED TO THE SWING WITH ADHESIVE TAPE. (VOGT & KUHN, 2012b)

2) *The Spring Pendulum*

A smartphone can also be used as a swinging mass to record the oscillation of a spring pendulum. A measurement example, which was recorded with an iPhone with a mass m = 0.152 kg, is shown in figure 13. It results in an almost perfect sinusoidal process, which offers similar learning opportunities to the results of the string pendulum:

a) Why do the accelerations vary around g and at what points of the swing is the maxima and minima located?

b) What is the duration of a period of an oscillation; how high is the spring constant of the spring used?

c) How strongly is the oscillation dampened?

Once again, examples related to items a) and b) will be discussed, whereby the dynamically determined spring constant will be compared with the result of a static measurement.

As regards a), as the pendulum slows down (motion away from the rest point) and as it speeds up (motion towards the rest point) inertia forces evolve, which are recorded in addition to the force of mass. The maximum accelerations occur at the top turning point of the swing, the minimum accelerations with the maximum extension of the springs.

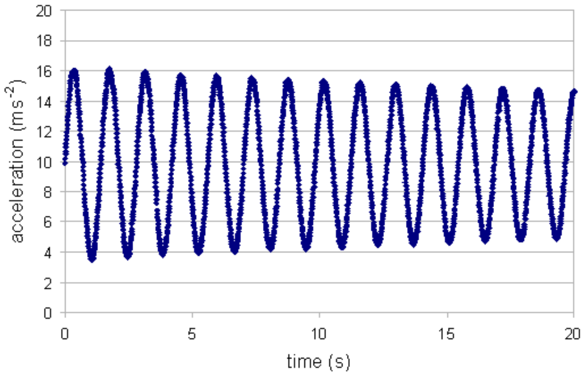

FIG. 13 DYNAMIC DETERMINATION OF SPRING CONSTANTS: CHRONOLOGICAL ACCELERATION PROCESS FOR A SPRING PENDULUM (KUHN & VOGT, 2012)

As regards b), on the basis of the data underlying in figure 13, thirteen complete oscillations occur in a time period Δt = 18.22 s. With

$$T = \frac{\Delta t}{n} = 2\pi\sqrt{\frac{m}{D}} \tag{7}$$

(n number of oscillations in time interval Δt) the spring constant D of the spring can be determined by applying the formula

$$D = \frac{4\pi^2 m}{\left(\frac{\Delta t}{n}\right)^2} = (3.055 \pm 0.003)\frac{\mathrm{N}}{\mathrm{m}}\,. \tag{8}$$

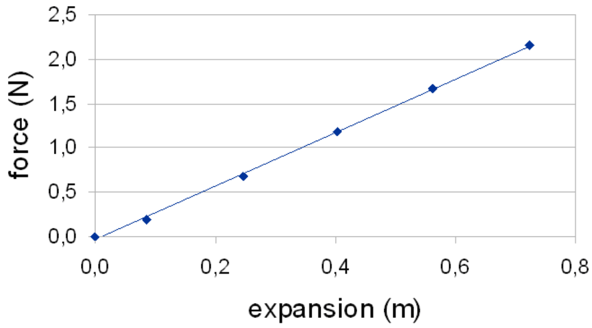

FIG. 14 STATIC DETERMINATION OF SPRING CONSTANTS: THE MASS FORCE F IMPACTING THE SPRING CARRIED AGAINST ITS AMPLITUDE X (KUHN & VOGT, 2012)

This value matches well with the result of a static measurement, in which the displacement x of the spring was examined in relation to the load F applied to it (forces resulting from the attached mass). For an elastic spring, Hooke's law of elasticity is applied

$$F = D \cdot x \tag{9}$$

i.e., carrying F to x results in a straight line, with the gradient corresponding to the spring constants (figure 14). A linear regression confirms the linear

relationship with an adjusted coefficient of determination close to one and determines the spring constant to be 3.02 Nm^{-1}.

3) *The Coupled Pendulum*

If two spring pendulums are coupled together by an attached mass (figure 15) and one of the two systems is set into motion, the oscillation performed by that pendulum soon also transfers over to the other pendulum. Provided that the springs used possess the same stiffness – i.e., the same spring constant - the first pendulum remains briefly motionless after some time; while its oscillation energy has been completely transferred over to the second pendulum. Then, the energy switches between the two pendulums, which is the reason that each of the pendulums makes a typical swing motion.

The oscillations of coupled pendulums of this kind can easily be recorded with the help of two smartphones which once again serve as mass for the pendulum (figure 15). A measurement example for a coupled mass of 100 g is shown in figure 16. When the acceleration values, and therefore the amplitudes, of one pendulum reach a maximum, the accelerations of the other pendulum correspond approximately to the acceleration of gravity, which equals a state of rest.

FIG. 15 EXPERIMENT SET-UP FOR A COUPLED PENDULUM (KUHN & VOGT, 2012)

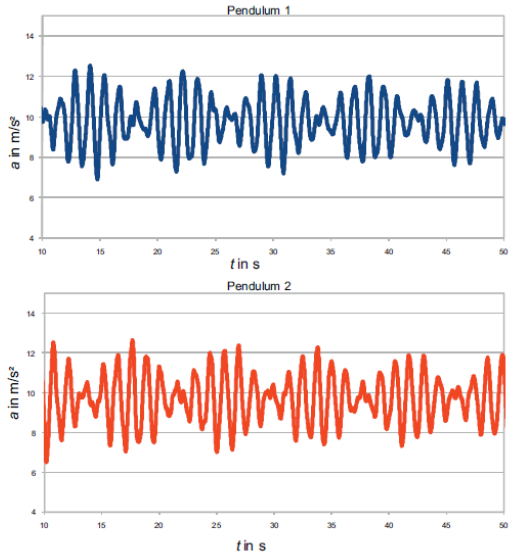

FIG. 16 ACCELERATION PROCESS OF BOTH COUPLED SPRING PENDULUMS (KUHN & VOGT, 2012)

The energy transfer happens even faster if the two pendulums are more strongly coupled together. This aspect can be examined in a subsequent experiment by varying the coupled mass.

There is a complication when analyzing the data, because the measurements of both smartphones cannot be started completely synchronously. In this case, the following method has proved successful: the person conducting the experiment starts the measurements on both smartphones separately and waits for the systems to reach a state of rest. Then he lightly taps the stand, which later clearly appears as a peak in both series of measurements. When analyzing the data, the time axes can then be moved so that the acceleration maxima resulting from the tap are positioned exactly on top of each other, corresponding to synchronization.

Radial Acceleration

The last experiment described in this article involves quantitatively exploring radial acceleration. A roof slat with a length of almost two meters is fixed to an electric motor of the kind that is often found in physics collections, e.g., for experiments with a semi-circular channel with two balls (figure 17). With the help of cable fixers, the smartphone is then fixed onto the wooden slat at a defined distance from the rotation center r so that[5] the axis points in the direction of

[5] In order to obtain a very precise specification of the distance to the rotation center, information on the location of the acceleration sensors within the smartphone must be obtained from the manufacturer. In the iPod touch (4G) the sensors are located beneath the home button; and a

radial acceleration. Figure 18 shows a measurement example for a distance from the rotation center of 86.5 cm. At the beginning of the measurement, the motor is switched off and the measured radial acceleration is close to zero (small deviations can arise because the smartphone is not positioned perfectly horizontally). After approx. 5 s, the motor is switched on; then the iPod moves with a constant velocity v.

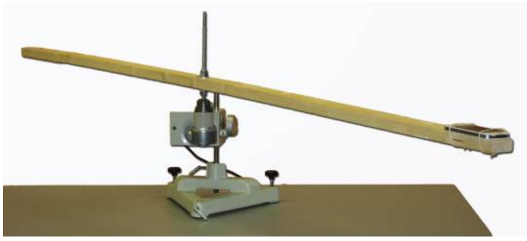

FIG. 17 EXPERIMENT SET-UP TO INVESTIGATE RADIAL ACCELERATION (VOGT & KUHN, 2013)

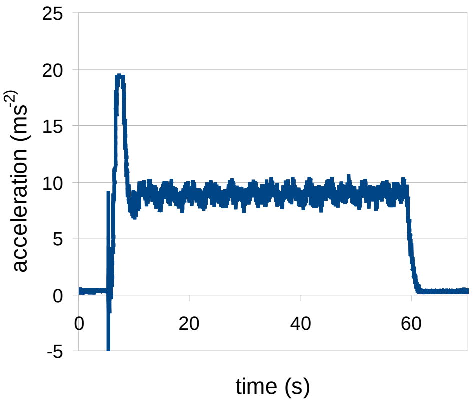

FIG. 18 MEASUREMENT EXAMPLE FOR A DISTANCE FROM THE ROTATION CENTER OF R = 0.865 M AND A DURATION OF CIRCULATION OF T = 38.2 S FOR 20 REVOLUTIONS (VOGT & KUHN, 2013)

If the acceleration values recorded at intervals of 12 s and 59 s are averaged, the value is calculated to be 8.69 ms^{-2}. This result can be compared with a conventional measurement, in which radial acceleration a is indirectly determined using the formula

$$a = \frac{v^2}{r} \, . \tag{10}$$

For this purpose, the time t is measured for a given number of revolutions n; while for the measurement example in figure 18, twenty revolutions occurred in 38.2 s. Taking into consideration the formula for the circumference and equation 10, radial acceleration is calculated to be

$$a = \frac{n^2 4\pi^2 r}{t^2} = \frac{20^2 \cdot 4\pi^2 \cdot 0.865 \text{ m}}{(38.2 \text{ s})^2} \approx 9.36 \frac{\text{m}}{\text{s}^2} , \tag{11}$$

description of the location for the iPhone 4G can be found in the Internet at http://www.ifixit.com/teardown/iphone-4-teardown/3130/2 (status: 07/2013).

which matches well with the result of the smartphone measurement.

As well as making specific measurements of radial acceleration, it is also possible to perform an experiment to verify equation 10 with this experiment set-up. Namely, by recording series of measurements, it is possible to confirm the proportionalities $a \sim v^2$ (for r = const.) and $a \sim 1/r$ (for v = const.). However, in the course of the velocity selection, it should be taken into account that the measurement range of the acceleration sensors installed in the smartphone is limited to ±2g.

Summary and Outlook

Even if it is often difficult to investigate real-life movements (e.g., in the area of sports) on the basis of acceleration measurements, the sensors integrated in smartphones can be used for a large number of experiments in the field of dynamics. In many cases, the use of a cell phone enables teachers to perform experiments in class, which was not previously possible, because accelerometers, for example, those supplied by Phywe or Pasco, are often not available in schools. In addition, pupils are familiar with the experiment tool smartphone, as they use the device in everyday life, and the apps can be operated intuitively without extensive instructions or training. Moreover, from an educational point of view, the impact of the smartphone as a status symbol should not be underestimated. It can be assumed that this effect will decrease as the media becomes more prevalent; however, this will never completely be the case-for example, a school physics collection would never include a class set of iPods (cost of 15 iPods or Smartphones currently approx. 3000 EUR).

Several quasi-experimental studies are planned to investigate whether the authenticity of the experiment tool, as described, has a positive impact on learning-related variables (motivation, performance, experimental skills).

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Patrik Vogt was born in 1978 in Germany. He got the university degree in Physics and Mathematics (junior high school teacher) at the University of Koblenz-Landau in 2003. In 2003-2010 he worked as a teacher in Herxheim and Kandel and received the Ph.D. degree in the field of physics education in 2010. After graduation, he was a postdoctoral fellow at the University of Koblenz-Landau and Kaiserslautern, then assistant professor at the University of Education Schwäbisch Gmünd. He is currently lecturer at the University of Education Freiburg and teaches physics and didactics of physics. His current research interests include context-based physics instruction, use of smartphones as an experimental tool and Very Low Frequency (VLF) radio phenomena.

Jochen Kuhn finished his university training to be a teacher for Physics and Mathematics in 1998 at the University of Koblenz-Landau, where he completed his PhD-Thesis in physics and physics education in 2002, too. In addition to graduation he had been working as high school teacher for over eight years before he became a scientific assistant at the physics education group of Prof. Dr. Andreas Müller (current position: Professor at the University Geneva) at the University of Koblenz-Landau in 2008. After finishing his habilitation thesis there in 2009, he received different offers as full professor in 2011. Since 2012 he has been full professor and head of the Physics Education Group at the University of Kaiserslautern.